Report No. RE-TR-63-7

COPY NO. № 20

AN OPTIMIZED ULTRA LOW FREQUENCY SHIELDED-LOOP ANTENNA

1 August 1963

U S ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA

DDC Availability Notice

Qualified requesters may obtain copies of this report from the Defense Documentation Center for Scientific and Technical Information, Cameron Station, Alexandria, Virginia 22314.

Destruction Notice

Destroy; do not return.

1 August 1963 Report No. RE-TR-63-7

AN OPTIMIZED ULTRA LOW FREQUENCY SHIELDED-LOOP ANTENNA

By

Harold B. Buie

DA Project No. 1-B-2-22901-A-204
AMCMS Code No. 5210.11.14600

Radiation Branch
Electromagnetics Laboratory
Directorate of Research and Development
U.S. Army Missile Command
Redstone Arsenal, Alabama

ABSTRACT

This report describes the design and construction of an optimized rectangular shielded-loop antenna employed as the receiving antenna for reception of VLF (20 kc) standard frequency broadcasts from the National Bureau of Standards, Boulder, Colorado. The receiving site is located at Redstone Arsenal, Alabama. This design affords an approximate 60 per cent increase in effective height with a 3-db increase in terminal output voltage over a conventional loop antenna. The antenna will tune from 14 to 34 kc and can be optimized at any frequency within this band with the proper value of gap loading. A current bibliography of loop antenna literature is also included.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

AN OPTIMIZED ULTRA LOW FREQUENCY SHIELDED-LOOP ANTENNA

I. INTRODUCTION

Renewed interest in the very low frequency region of the spectrum was brought about recently when the National Bureau of Standards Laboratory at Boulder, Colorado, began transmitting standard-frequency broadcasts on 20 kc, with 15 watts effective radiated power. A review of the available literature revealed that virtually no work had been done in this region of the spectrum since the early "spark gap" days. It seemed that subsequent investigators had jumped over this part of the band. In those days circuit components would have been so unwieldy that working in that range would have been very difficult.

Now that component technology has provided much smaller components, it is logical that good techniques previously developed in the 1920's and 1930's be reviewed for possible reapplication. This design came from the "lost art" and is based on a paper[22] by R. E. Burgess.

A shielded loop is indicated in view of the expected high ambient noise level in the 20 kc region of the spectrum.

II. DISCUSSION

The general loop analysis is treated comprehensively in other literature and is omitted here. A conventional shielded-loop antenna utilizes an open circuited shield and usually has an insulator to protect the inner loop winding. The concept presented here utilizes capacitive loading of the gap to effect an increase in the loop output voltage. The following assumptions are made regarding the voltages induced in the screen and loop, and the mutual currents so produced:

A. The screen and loop each have an induced e.m.f. independent of the other, and proportional to the area turns and magnetic intensity perpendicular to the plane of the loop/screen--the gap (point at which the screen is separated) being sufficiently small not to affect the screen voltage.

B. The screen and loop are inductively coupled only, the coupling being expressed by mutual inductance M.

C. The linear dimensions of the screen are small compared to a wavelength, and the currents in the screen and loop can be considered uniform. (Without this assumption the treatment requires application of transmission line theory.)

Considering the aforementioned assumptions, the equivalent circuit is as shown in Figure 1. Z_1 and Z_2 are the total impedances around the screen and loop circuit. $\mathcal{E}_1$ and $\mathcal{E}_2$ are the induced e.m.f.'s; the corresponding instantaneous currents are i_1 and i_2. The close proximity of the screen increases the self capacitance, and thus the self resonant frequency of the loop. Conventional loops minimize this effect by running the loop wire centrally in the screen, which is usually aluminum or copper tubing. A shielded loop can be optimized by using the maximum number of turns and still have the self resonant frequency sufficiently high (approximately twice the operating frequency). By application of gap loading, a value of x_C can be found that will be reflected into the loop as x_L by transformer action. This is effectively an increase in loop turns. An increase in output voltage will result since:

$$\mathcal{E}_o = h_e \text{ x (applied field volts/meter)}$$

and:

$$h_e \text{ (effective height)} = \frac{2\pi N_2 A}{\lambda} \qquad (1)$$

where:

for $A << 0.001\,\lambda^2$

A = mean area per turn

N_2 = number of loop turns

λ = wavelength

The ratio of e.m.f.'s, $\frac{\mathcal{E}_2}{\mathcal{E}_1}$ is denoted by N and is assumed real. This ratio approaches the value N_2 as the cross section of the screen decreases.

The Kirchoff equations for the two circuits are:

screen

$$\ell_1 = Z_1 i_1 + j\omega M i_2 \tag{2}$$

loop

$$\ell_2 = N\ell_1 = Z_2 i_2 + j\omega M i_1 \tag{3}$$

where

$$\omega = 2\pi \text{ frequency} \tag{4}$$

The solutions for the currents are:

screen

$$i_1 = \ell_1 \frac{Z_2 - j\omega NM}{\omega^2 M^2 + Z_1 Z_2} = \frac{\ell_1 - \frac{j\omega M}{Z_2} \ell_2}{Z_1 + \frac{\omega^2 M^2}{Z_2}} \tag{5}$$

loop

$$i_2 = \ell_1 \frac{NZ_1 - j\omega M}{\omega^2 M^2 + Z_1 Z_2} = \frac{\ell_2 - \frac{j\omega M}{Z_1} \ell_1}{Z_2 + \frac{\omega^2 M^2}{Z_1}} \tag{6}$$

In the second form of each current the numerator is the effective voltage and the denominator the effective impedance. In the numerator of equation 5, ℓ_2 corresponds to the original field and $-j \frac{\omega M}{Z_1} \ell_1$ to the secondary field produced by the screen.

Mutual inductance M may be defined as the linkage between the loop and the magnetic flux produced by the unit current in the screen. Since each loop turn links with screen flux, this linkage is equal to (number of turns) x (flux produced by the unit current in the screen); therefore:

$$M = N_2 L_1 \text{ or } K^2 L_2 = N^2 L_1 \tag{7}$$

where K is the coefficient of coupling between the screen and loop, L_1 and L_2 respectively. K may be calculated since at these frequencies mutual inductance M can be determined with an inductance bridge.

$$M = \frac{L\ \text{aiding} - L\ \text{opposing}}{4} \qquad (8)$$

Measuring the total inductance of the primary (screen) and secondary (loop) inductances in series aiding and then in series opposing, K may be found by:

$$K = \frac{M}{\sqrt{L_1 L_2}} \qquad (9)$$

The optimum gap load value of C_1 is given as:

$$C_1\ \text{opt.} = C\ \frac{1 - K\sqrt{\dfrac{1 + K^2 P}{K^2 + P}}}{1 - K^2} \qquad (10)$$

where:

C = value of capacitance required to tune the screen to frequency of interest.

$$P = \frac{Q}{Q_2} = \frac{Q\ \text{of screen ckt.}}{Q\ \text{of loop ckt.}} \qquad (11)$$

III. RESULTS

Figure 2 provides a convenient method of determining actual values of the many variables encountered in this design. The loop inductance L_1, Q_1 of the screen, Q_2 of the loop, self resonant, distributed capacity, optimum value of gap loading, and increase in pickup due to gap loading have all been measured using this test arrangement.

Figure 3 shows the physical configuration of the shielded loop antenna and some of its construction details.

Figure 4 is an aerial view of the receiving site. The optimized shielded-loop antenna can be seen mounted between the telephone pole on the right of the photograph. The antenna is oriented so that the maximum of the radiation pattern is directed toward Boulder, Colorado.

Figure 5 is a close-up photograph of the moulded plastic gap with the loading capacitors and the lighting protection mounted. The

lighting protection consists of a needle spark gap set to protect the capacitors. The spark gap is adjusted for a clearance which is dependant on the working voltage of the capacitors used for loading. The details of the moulded gap and its construction are given in Figure 6. The gap loading capacity versus loop output voltage is shown in Figure 7. From these measurements, the optimization by gap loading is confirmed. The optimum number of turns is determined by measurements plotted in Figure 8.

These measurements can be accomplished by approximating the shield with aluminum foil and laying the loop out on the ground. The ground will not effect the self resonant frequency since it is already shielded at ground potential with the foil. The data are taken as the number of turns is increased.

In Figure 9 the final loop design parameter measurements provide a series of conditions which are plotted so that a condition number can be given to the choice of a particular operating point. Condition No. 13 was given to this design; the gap load was 0.2 microfarad, Q_2 is 18.2, the loop inductance is 9.5 millihenrys (no gap load), with gap loaded the loop inductance is 24 millihenrys, the capacitance required to resonate the loop at 20 kc with the gap loaded is 0.003 microfarad, and a 3.92-db gain over a conventional shielded-loop antenna was realized.

IV. CONCLUSIONS

This design was fabricated and utilized with a 20 kc WWVL receiving system designed by the Radiation Branch of the Electromagnetics Laboratory, AMICOM. The system was operated successfully by receiving and recording signals broadcast from the National Bureau of Standards 20 kc WWVL station located at Boulder, Colorado.

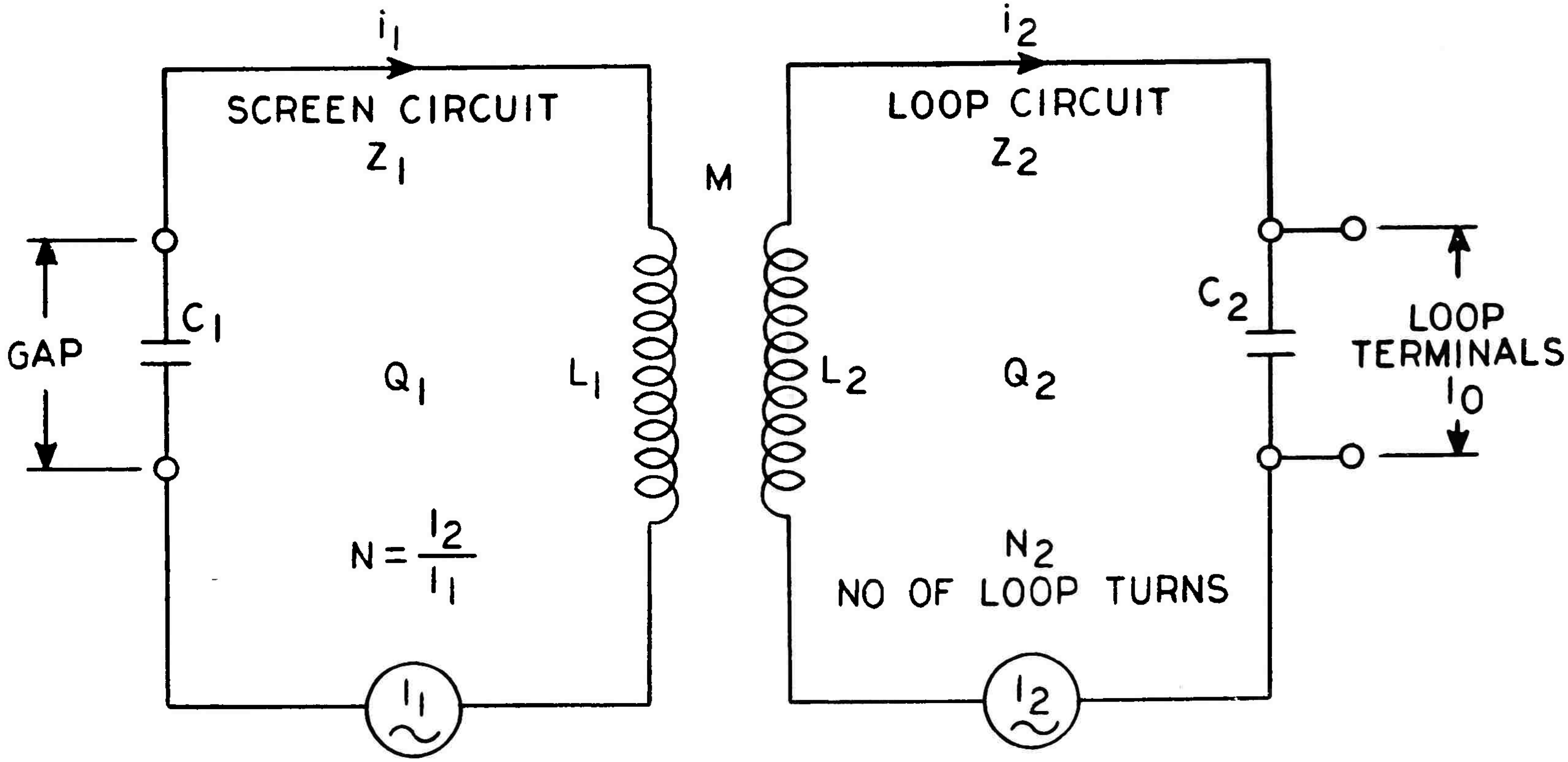

Figure 1. LOOP/SCREEN EQUIVALENT CIRCUIT

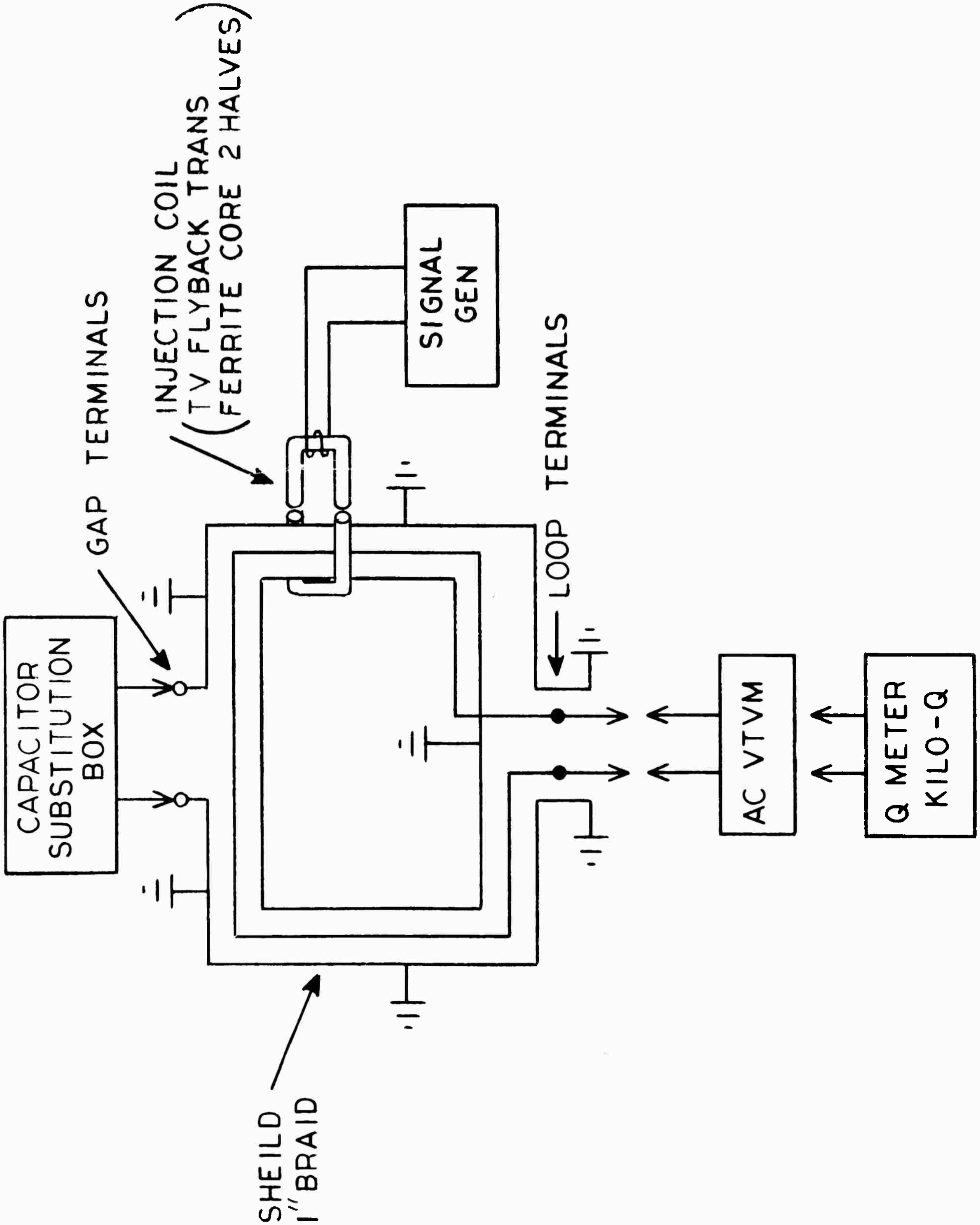

Figure 2. LOOP TEST EQUIPMENT SET-UP

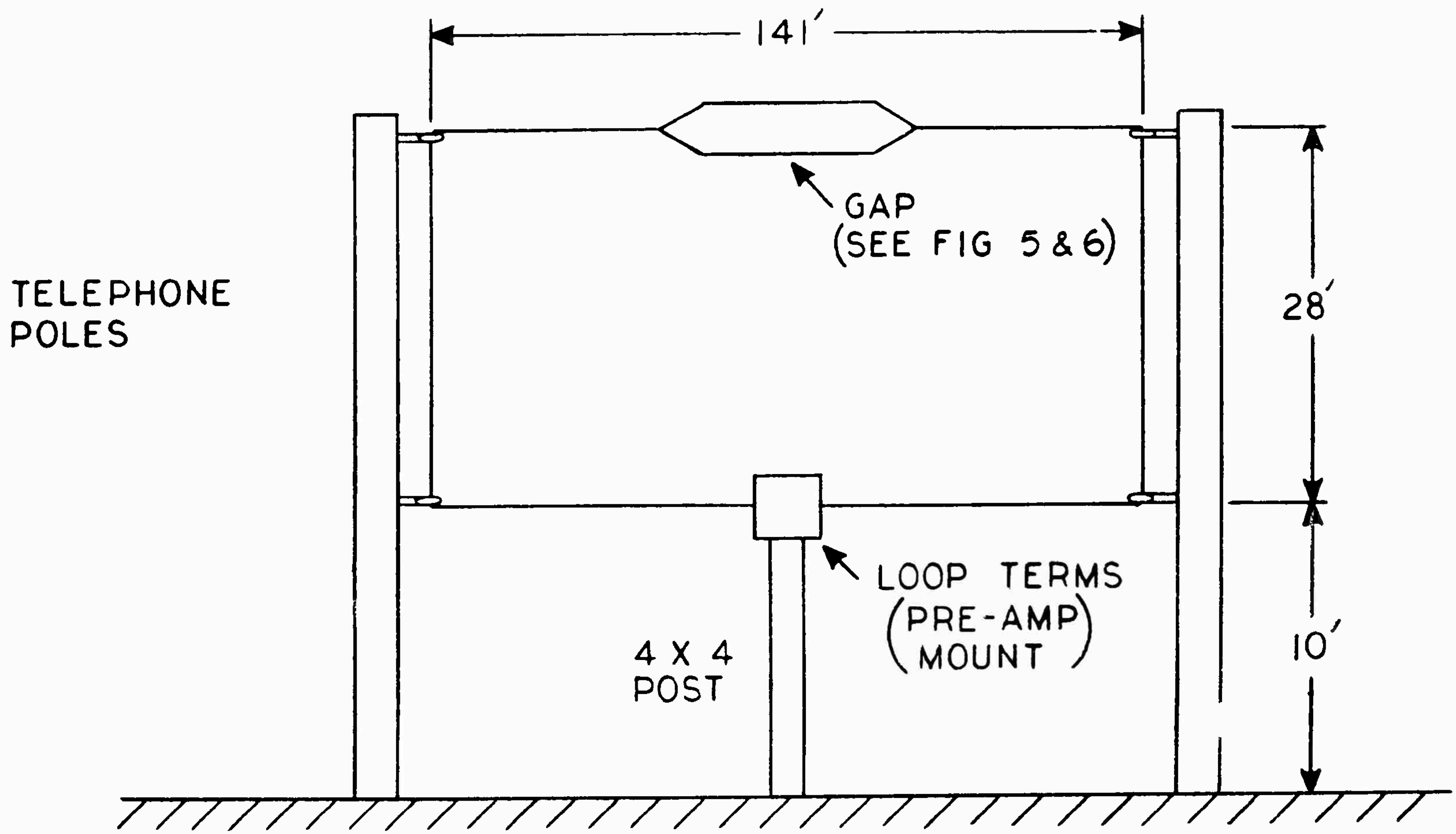

Figure 3. LOOP CONFIGURATION

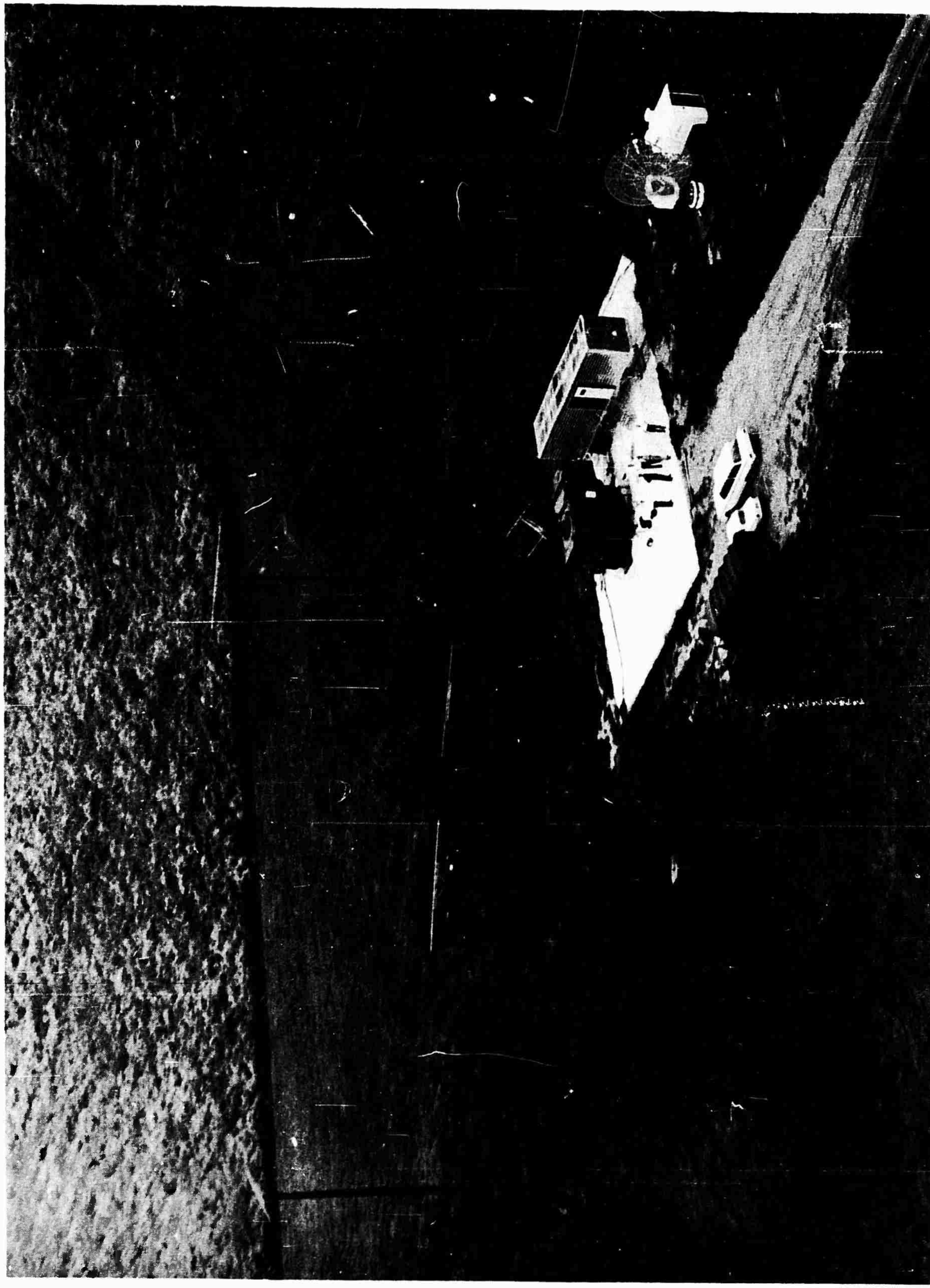

Figure 4. AERIAL VIEW OF RECEIVING SITE

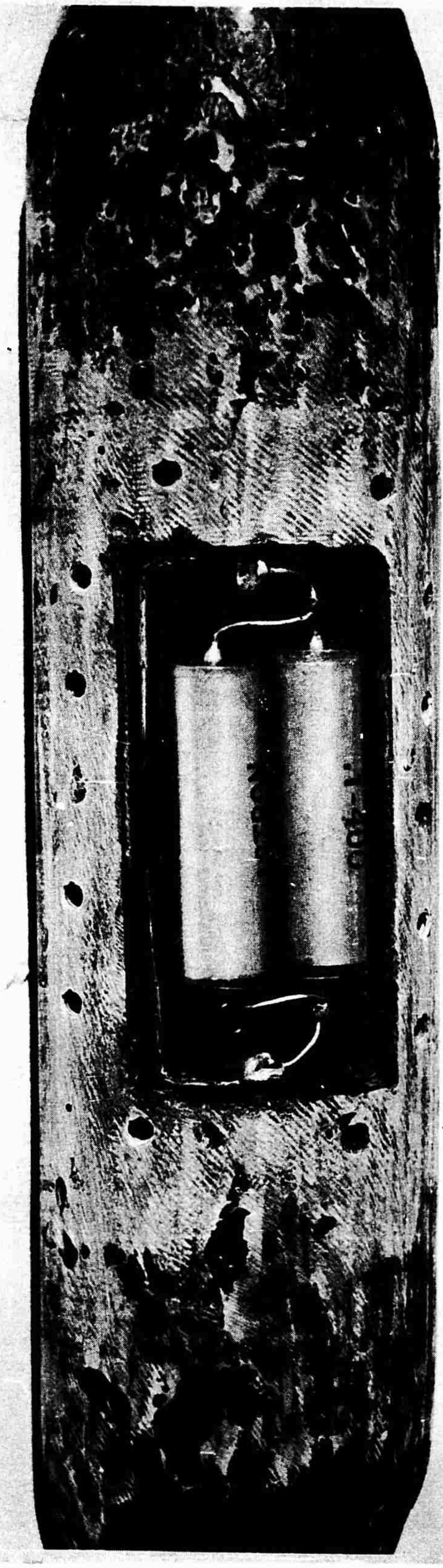

Figure 5. GAP LOADING MOUNTING ARRANGEMENT

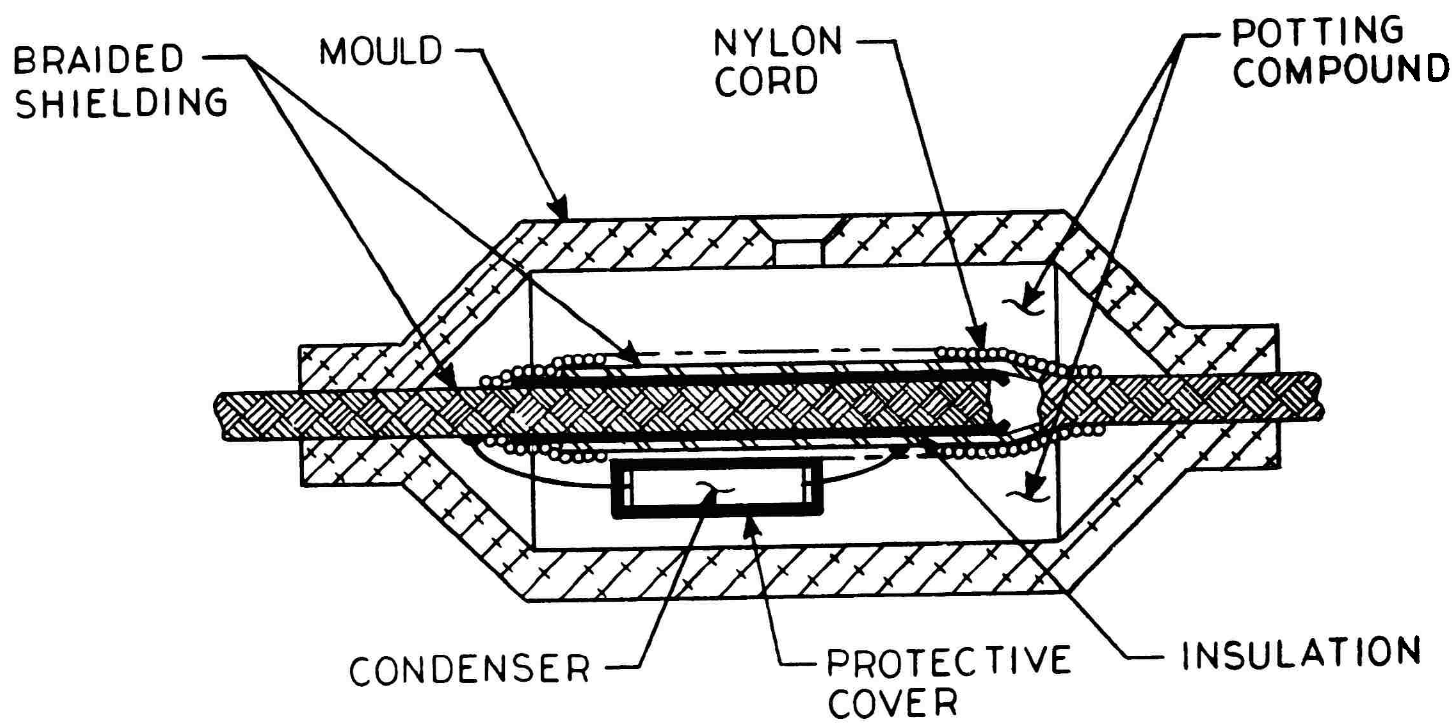

Figure 6. MOULDED PLASTIC GAP MOUNTING ARRANGEMENT

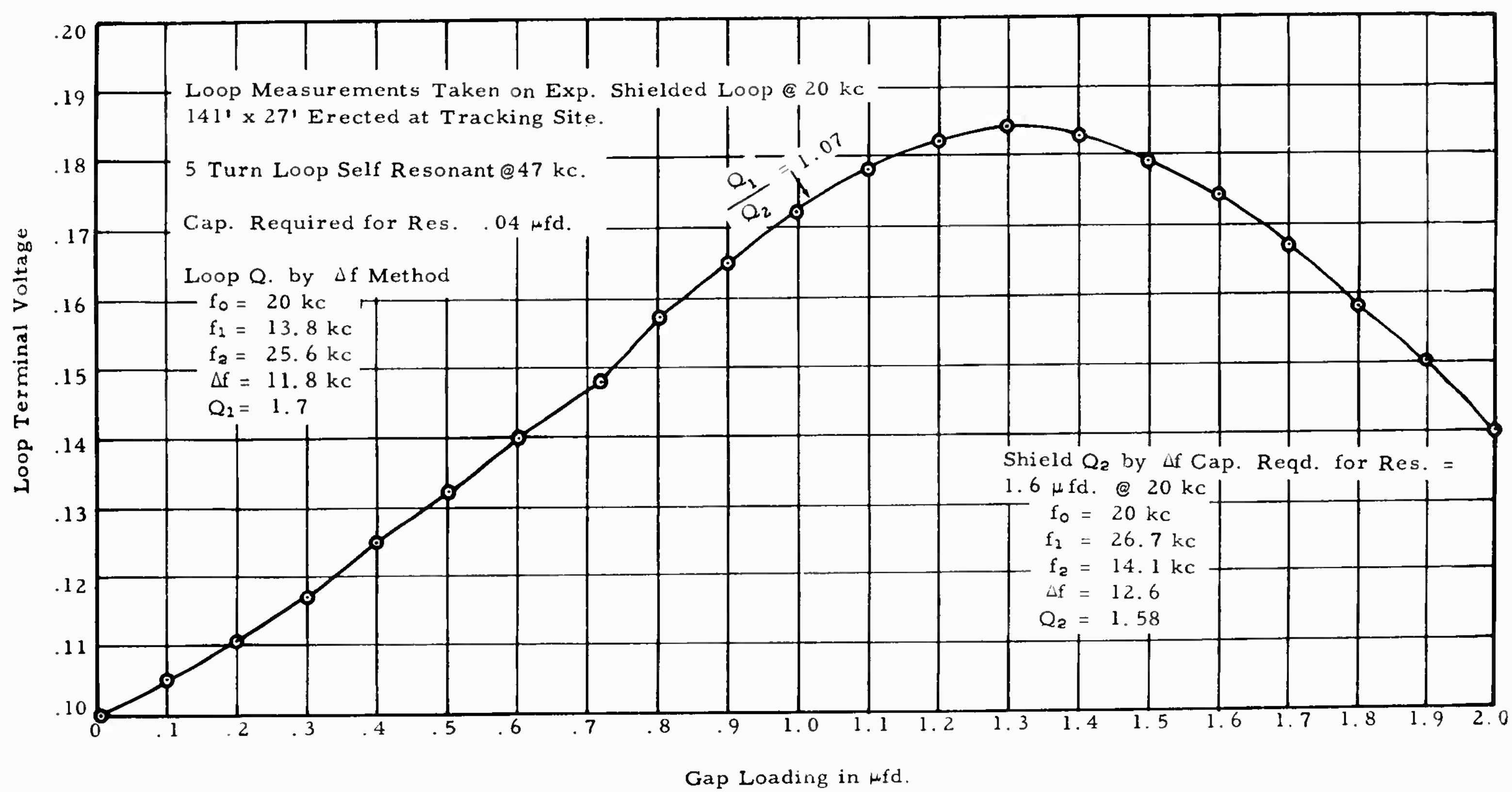

Figure 7. GAP LOADING CAPACITY VERSUS LOOP TERMINAL VOLTAGE

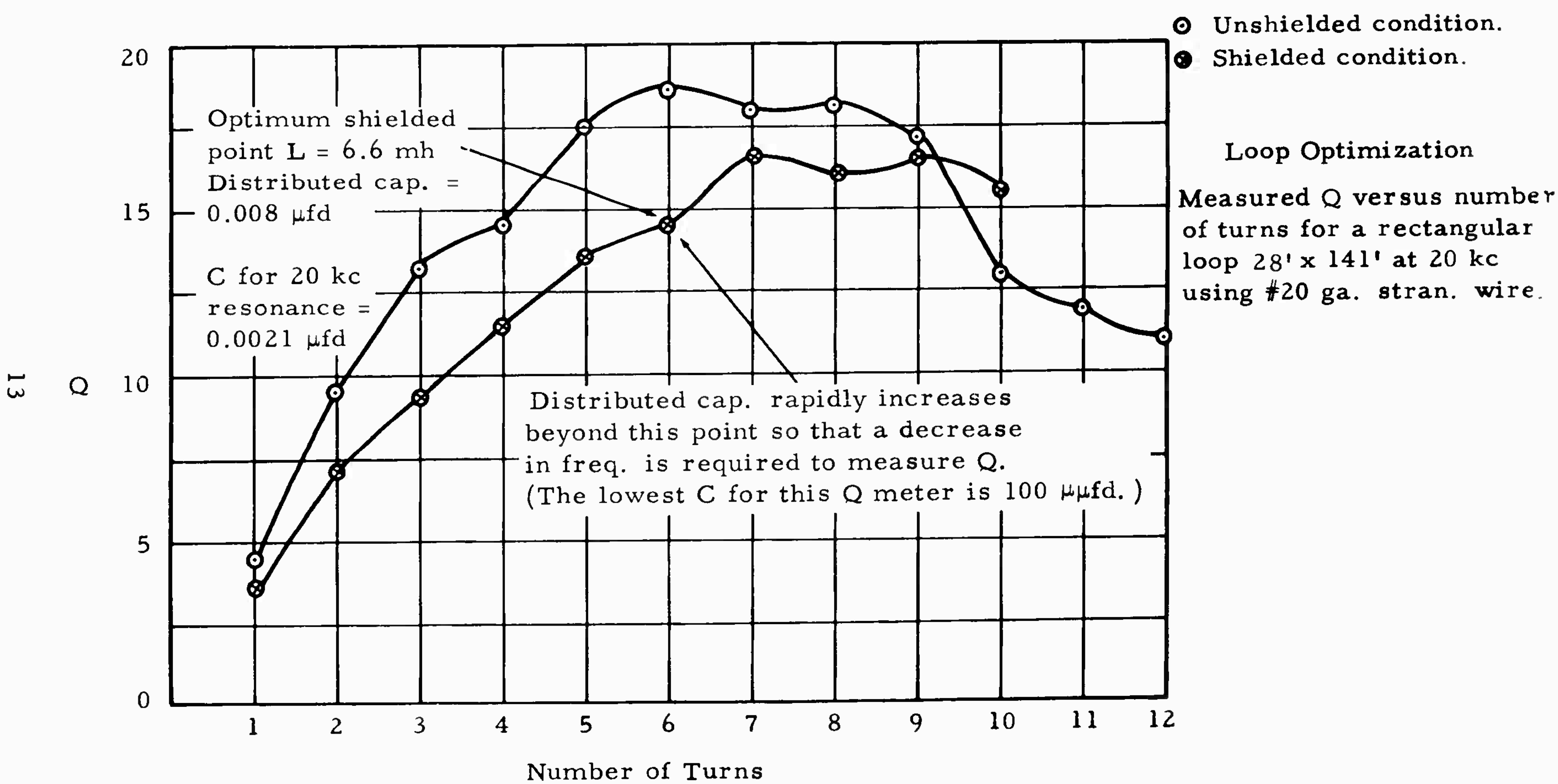

Figure 8. LOOP TURNS VERSUS Q

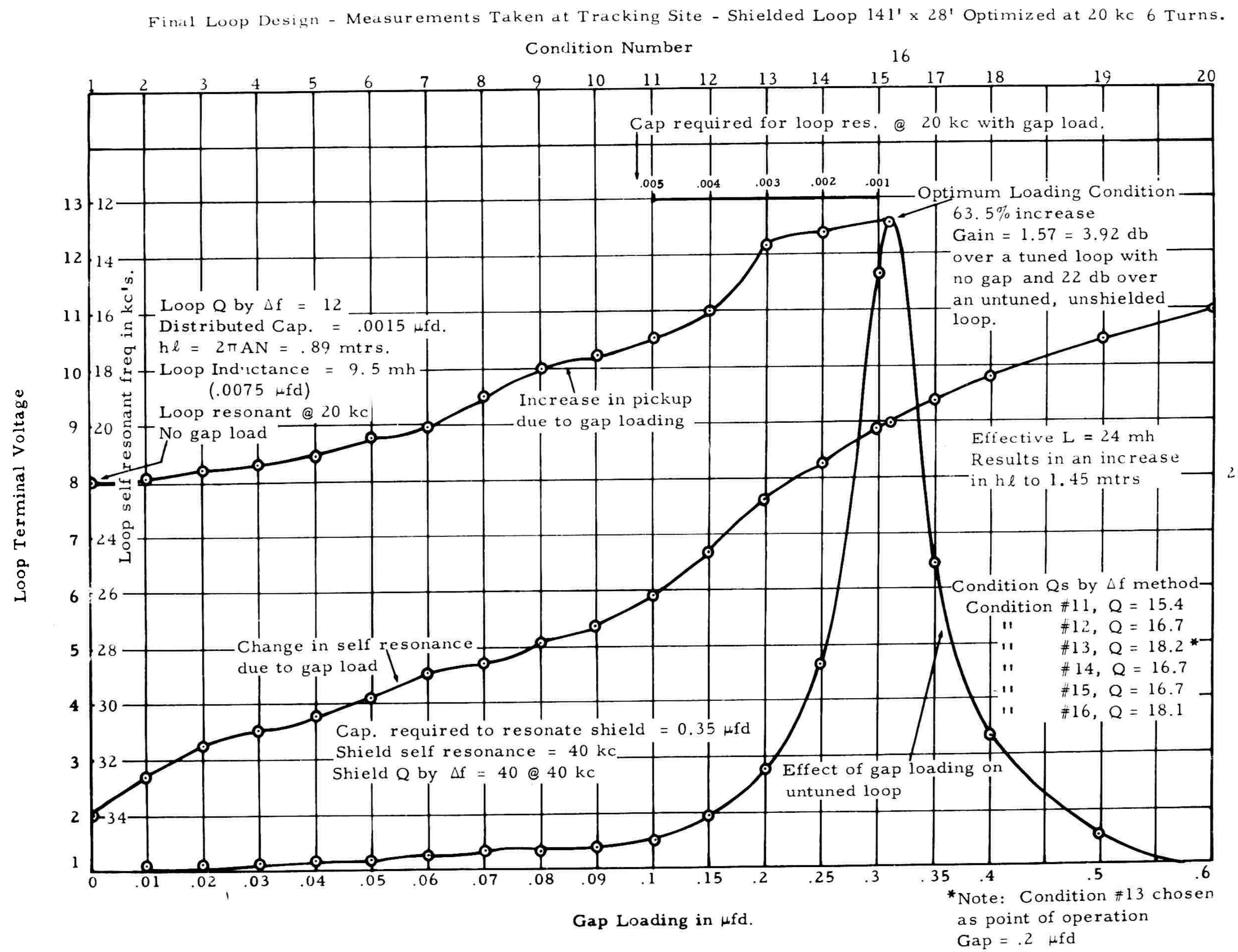

Figure 9. FINAL LOOP DESIGN PARAMETERS

BIBLIOGRAPHY

1. "Folded Dipoles and Loops", C.W. Harrison, R.W.P. King, IRE Trans. on Ant. and Prop., Vol. AP-9, March 1961.

2. "Rectangular Loop Antenna As Dipole", R. King, IRE Trans. on Ant. and Prop., Vol. AP-6, January 1959.

3. "Corner Driven Coupled Square Loop Antenna", Sprasad Can Journal of Physics, Vol. 32, December 1959.

4. "Terminated Circular Loop Aerial", S. Balarum, RAO Electro-Technology (formerly Electronic and Radio Engineer), Vol. 34, September 1957.

5. "Ferromagnetic Loop Aerials for Kilometric Waves", J.S. Belrose, Wireless Engineer, Vol. 32, February 1955.

6. "Spaced Loop Aerials", F. Horner, Vol. 25, Wireless Engineer, September 1948.

7. "Properties of Loop Aerials", F. Horner, Vol. 25, Wireless Engineer, August 1948.

8. "An Experimental Spaced Loop Direction Finder for High Frequency", F. Horner, Jour. Inst. of Electrical Engrs., Vol. 94, pt. III No. 28, 1948.

9. "The Development and Study of a Practical Spaced Loop Direction Finder for High Frequency", W. Ross, Jour. Inst. of Elec. Engr., Vol. 94, pt. III No. 28, 1947.

10. "Design Values for Loop Antenna Input Ckts", J.E. Broder and V.J. Young, Proc. IRE, Vol. 35, No. 5, May 1947.

11. "Special Aspects of Balanced Shielded Loops", L.L. Libby, Vol. 34, No. 9, September 1946, Proc. IRE.

12. "Low Impedance Loop Antenna for Broadcast Receivers", L.O. Vladimir, Electronics, Vol. 19, No. 9, September 1946.

13. "Iron Cored Loop Receiving Aerial", R.E. Burgess, Wireless Engr., Vol. 23, June 1946.

14. "Coaxial Feed FM Loop Antennas", A.G. Kandoian, Electronic Ind., Vol. 5, No. 5, May 1946.

15. "Loop Antenna Coupling Transformer Design", W.S. Baschman, Proc. IRE, Vol. 33. 12, December 1945.

16. "Square Loop FM Antenna", T. P. Taylor, Vol. 18, No. 3, March 1945, Electronics.

17. "Airloop Antenna", Vol. 4, No. 10, October 1945.

18. "Loop Antenna with Uniform Current", by D. Foster, Proc. IRE, Vol. 32, No 10, October, 1944.

19. "Circular Loop Antenna at UHF", J. B. Sherman, Proc. IRE, Vol. 32, No. 9, September 1944.

20. "Reactance and Effective Height of Screened Loop Aerials", R.E. Burgess, Wireless Engineer, Vol. 121, No. 248, May 1944.

21. "Method of Measuring Effectiveness of Electro-static Loop Shielding", D.E. Foster and C.W. Finigan, Proc. IRE, Vol. 31, No. 6, June 1943.

22. "The Screened Loop Aerial", R.E. Burgess, Wireless Engineer, Vol. 116, October 1939.

23. "The Application of Transmission Line Theory to Closed Aerials", F.M. Colebrook, Jour. IEE, Vol. 83, 1938.

24. "Shielded Loop for Noise Reduction in Broadcast Receivers", S. Goldman, Electronics, Vol. II, No. 10, October 1938.

25. "Theory of Loop Antennas with Leakage Between the Turns", P.B. Taylor, Proc. IRE, Vol. 25, No. 12, December 1937.

26. "A Study of Litz Wire Coils for LF and RF Transformers", D. Grimes and W.S. Bared, Vol. 6, December 1933, Electronics.

27. "The Establishment of a General Formula for the Inductance of a Single Turn Circuit of Any Shape", V. I. Bashenoff, Wireless Engineer, Vol. 6, No. 68, May 1929.

28. "The Theory of the Frame Aerial", R.L. Smith, Rose Vol. 23, No. 7, August 15, 1928, Wireless World.

29. "The Screening of Radio Receiving Apparatus", R.H. Barfield, Journ. IEE, Vol. 62, 1924.

30. "Effective Resistance of Inductance Coils at Radio Frequencies", S. Butterworth, Wireless Engineer, Vol. 3, August 1926.

APPROVED:

Waite H Todd

WAITE H. TODD
Chief, Radiation Branch

D. E. Rowe

D. E. ROWE
Director, Electromagnetics Laboratory

DISTRIBUTION

		No. Copies
U.S. Army Missile Command Distribution List B (15 April 1963)		96
AMSMI -R,	Mr. McDaniel	1
-RE,	Mr. Buie	6
-RFS,	Dr. McCorkle	1
-RR		1
-RK		1
-RG		1
-RL		1
-RS		1
-RT		1
-RBL		5
-RAP		1
U. S. Army Missile Command Distribution List A for Technical Reports (11 March 1963)		103

AD____________ Accession No.____________

Army Missile Command, Directorate of Research and Development, Electromagnetics Laboratory, Redstone Arsenal, Alabama
AN OPTIMIZED ULTRA LOW FREQUENCY SHIELDED-LOOP ANTENNA - Harold B. Buie

Army Msl Cmd RE-TR-63-7, 1 Aug 63, 18 pp - illus. Unclassified Report

The design and construction of an optimized rectangular shielded-loop antenna used as the receiving antenna for reception of VLF (20 kc) standard frequency broadcasts from the NBS, Boulder, Colorado is described. The receiving site is at Redstone Arsenal. An increase in effective height and terminal output is afforded by this design. A bibliography of loop antennas is included.

UNCLASSIFIED

1. Loop antennas--Bibliography
2. Loop antennas--Configuration
3. Loop antennas--Construction
4. Loop antennas--Design
5. Loop antennas--Shielding

I. Buie, Harold B.

DISTRIBUTION: Copies obtainable from DDC, Cameron Station (Bl. 5), Alexandria, Virginia, 22314.

AD____________ Accession No.____________

Army Missile Command, Directorate of Research and Development, ElectromagneticsLaboratory, Redstone Arsenal, Alabama
AN OPTIMIZED ULTRA LOW FREQUENCY SHIELDED-LOOP ANTENNA - Harold B. Buie

Army Msl Cmd RE-TR-63-7, 1 Aug 63, 18 pp - illus. Unclassified Report.

The design and construction of an optimized retangular shielded-loop antenna used as the receiving antenna for reception of VLF (20 kc) standard frequency broadcasts from the NBS, Boulder, Colorado is described. The receiving site is at Redstone Arsenal. An increase in effective height and terminal output is afforded by this design. A bibliography of loop antennas is included.

UNCLASSIFIED

1. Loop antennas--Bibliography
2. Loop antennas--Configuration
3. Loop antennas--Construction
4. Loop antennas--Design
5. Loop antennas--Shielding

I. Buie, Harold B.

DISTRIBUTION: Copies obtainable from DDC, Cameron Station (Bl. 5), Alexandria, Virginia, 22314.

AD____________ Accession No.____________

Army Missile Command, Directorate of Research and Development, Electromagnetics Laboratory, Redstone Arsenal, Alabama
AN OPTIMIZED ULTRA LOW FREQUENCY SHIELDED-LOOP ANTENNA - Harold B. Buie

Army Msl Cmd RE-TR-63-7, 1 Aug 63, 18 pp - illus. Unclassified Report

The design and construction of an optimized rectangular shielded-loop antenna used as the receiving antenna for reception of VLF (20 kc) standard frequency broadcasts from the NBS, Boulder, Colorado is described. The receiving site is at Redstone Arsenal. An increase in effective height and terminal output is afforded by this design. A bibliography of loop antennas is included.

UNCLASSIFIED

1. Loop antennas--Bibliography
2. Loop antennas--Configuration
3. Loop antennas--Construction
4. Loop antennas--Design
5. Loop antennas--Shielding

I. Buie, Harold B.

DISTRIBUTION: Copies obtainable from DDC, Cameron Station (Bl. 5), Alexandria, Virginia, 22314.

AD____________ Accession No.____________

Army Missile Command, Directorate of Research and Development, ElectromagneticsLaboratory, Redstone Arsenal, Alabama
AN OPTIMIZED ULTRA LOW FREQUENCY SHIELDED-LOOP ANTENNA - Harold B. Buie

Army Msl Cmd RE-TR-63-7, 1 Aug 63, 18 pp - illus. Unclassified Report.

The design and construction of an optimized rectangular shielded-loop antenna used as the receiving antenna for reception of VLF (20 kc) standard frequency broadcasts from the NBS, Boulder, Colorado is described. The receiving site is at Redstone Arsenal. An increase in effective height and terminal output is afforded by this design. A bibliography of loop antennas is included.

UNCLASSIFIED

1. Loop antennas--Bibliography
2. Loop antennas--Configuration
3. Loop antennas--Construction
4. Loop antennas--Design
5. Loop antennas--Shielding

I. Buie, Harold B.

DISTRIBUTION: Copies obtainable from DDC, Cameron Station (Bl. 5), Alexandria, Virginia, 22314.

AD____________ Accession No.____________

Army Missile Command, Directorate of Research and Development, Electromagnetics Laboratory, Redstone Arsenal, Alabama

AN OPTIMIZED ULTRA LOW FREQUENCY SHIELDED-LOOP ANTENNA - Harold B. Buie

Army Msl Cmd RE-TR-63-7, 1 Aug 63, 18 pp - illus. Unclassified Report

The design and construction of an optimized rectangular shielded-loop antenna used as the receiving antenna for reception of VLF (20 kc) standard frequency broadcasts from the NBS, Boulder, Colorado is described. The receiving site is at Redstone Arsenal. An increase in effective height and terminal output is afforded by this design. A bibliography of loop antennas is included.

UNCLASSIFIED

1. Loop antennas--Bibliography
2. Loop antennas--Configuration
3. Loop antennas--Construction
4. Loop antennas--Design
5. Loop antennas--Shielding

I. Buie, Harold B.

DISTRIBUTION: Copies obtainable from DDC, Cameron Station (Bl. 5), Alexandria, Virginia, 22314.

AD____________ Accession No.____________

Army Missile Command, Directorate of Research and Development, Electromagnetics Laboratory, Redstone Arsenal, Alabama

AN OPTIMIZED ULTRA LOW FREQUENCY SHIELDED-LOOP ANTENNA - Harold B. Buie

Army Msl Cmd RE-TR-63-7, 1 Aug 63, 18 pp - illus. Unclassified Report.

The design and construction of an optimized retangular shielded-loop antenna used as the receiving antenna for reception of VLF (20 kc) standard frequency broadcasts from the NBS, Boulder, Colorado is described. The receiving site is at Redstone Arsenal. An increase in effective height and terminai output is afforded by this design. A bibliography of loop antennas is included.

UNCLASSIFIED

1. Loop antennas--Bibliography
2. Loop antennas--Configuration
3. Loop antennas--Construction
4. Loop antennas--Design
5. Loop antennas--Shielding

I. Buie, Harold B.

DISTRIBUTION: Copies obtainable from DDC, Cameron Station (Bl. 5), Alexandria, Virginia, 22314.

AD____________ Accession No.____________

Army Missile Command, Directorate of Research and Development, Electromagnetics Laboratory, Redstone Arsenal, Alabama

AN OPTIMIZED ULTRA LOW FREQUENCY SHIELDED-LOOP ANTENNA - Harold B. Buie

Army Msl Cmd RE-TR-63-7, 1 Aug 63, 18 pp - illus. Unclassified Report

The design and construction of an optimized rectangular shielded-loop antenna used as the receiving antenna for reception of VLF (20 kc) standard frequency broadcasts from the NBS, Boulder, Colorado is described. The receiving site is at Redstone Arsenal. An increase in effective height and terminal output is afforded by this design. A bibliography of loop antennas is included.

UNCLASSIFIED

1. Loop antennas--Bibliography
2. Loop antennas--Configuration
3. Loop antennas--Construction
4. Loop antennas--Design
5. Loop antennas--Shielding

I. Buie, Harold B.

DISTRIBUTION: Copies obtainable from DDC, Cameron Station (Bl. 5), Alexandria, Virginia, 22314.

AD____________ Accession No.____________

Army Missile Command, Directorate of Research and Development, Electromagnetics Laboratory, Redstone Arsenal, Alabama

AN OPTIMIZED ULTRA LOW FREQUENCY SHIELDED-LOOP ANTENNA - Harold B. Buie

Army Msl Cmd RE-TR-63-7, 1 Aug 63, 18 pp - illus. Unclassified Report.

The design and construction of an optimized rectangular shielded-loop antenna used as the receiving antenna for reception of VLF (20 kc) standard frequency broadcasts from the NBS, Boulder, Colorado is described. The receiving site is at Redstone Arsenal. An increase in effective height and terminal output is afforded by this design. A bibliography of loop antennas is included.

UNCLASSIFIED

1. Loop antennas--Bibliography
2. Loop antennas--Configuration
3. Loop antennas--Construction
4. Loop antennas--Design
5. Loop antennas--Shielding

I. Buie, Harold B.

DISTRIBUTION: Copies obtainable from DDC, Cameron Station (Bl. 5), Alexandria, Virginia, 22314.